Renewable and Sustainable Energy Reviews 13 (2009) 1326–1337

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessing total and renewable energy in Brazilian automotive fuels. A life cycle inventory (LCI) approach

Márcio de Almeida D'Agosto *, Suzana Kahn Ribeiro

Transportation Engineering Program, Federal University of Rio de Janeiro, Cidade Universitária, Centro de Tecnologia, bloco H, sala 111, CEP: 21.941-972, Rio de Janeiro, RJ, Brazil

A R T I C L E I N F O

Article history:
Received 23 May 2008
Accepted 21 August 2008

Keywords:
Renewable energy
Total energy
Transportation
Life cycle
Biofuels

A B S T R A C T

This article uses a first approach LCI procedure to evaluate total and renewable energy and CO_2 emissions in Brazilian automotive fuels life cycle (LC). The LC model is structured and modular, capable of being successively refined if necessary. The procedure is applied to passenger car use in urban traffic, comparing three fuels used in Brazil (gasoline with 25% ethanol, pure ethanol and compressed natural gas), considering their use in urban traffic in the city of Rio de Janeiro. An in deep research was made to collect representative and unpublished data of Brazilian automotive fuels LC reality, what is considered a main contribution. The results show where specific advantages occur, particularly in the use of renewable fuels made from biomass, an option already practiced and appropriate for Brazilian reality. The use of gasoline with 25% ethanol shows the lowest total energy consumption for the LC, with similar performance to that of compressed natural gas and 36% better than ethanol from sugarcane. However, the last alternative has the advantage of depending almost exclusively on renewable energy (93%) and producing less net CO_2 emissions.

Contents

1. Introduction

Energy consumption for transportation in Brazil grew 17% between 1996 and 2005, of which 90% was due to roadway transportation, involving petroleum derivatives (81%), compressed natural gas (CNG) (4%) and ethanol from sugarcane (15%), all widely available alternatives [1]. However, the growing social awareness of sustainable development implies making informed choices among these alternatives considering their energy efficiency and the amount of renewable energy (RE) along the entire supply chain, not just in their final use, as is the current practice [2].

* Corresponding author. Tel.: +55 21 2562 8171; fax: +55 21 2562 8131.
E-mail address: dagosto@pet.coppe.ufrj.br (M.d.A. D'Agosto).

1364-0321/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2008.08.008

Table 1
Summary of the references chosen on application of LCA to energy sources for road transport

Authors	Year	Place	Application of the technique	Objective/application	Scope						Functional unit	Allocation criterion	Categories of impacts
					Dimensions			Extent					
					Width	Length	Depth	Temporal	Geographic	Technological			
Furuholt [4]	1995	Norway	Complete: 4 phases of the LCA	Gasoline, gasoline with MTBE and diesel oil	1st level	Supply chain	Energy, CO_2, NO_X, SO_X, COV	Short-term (year of the study)	Proprietary data	Usual technology on the study date	Liters	Energy equivalent	5 categories[2]
Wang et al. [5]	1997	USA	Partial: LCI and interpretation	E85, E10 and gasoline	1st level	Supply chain and final use	Energy, CO_2, CH_4, N_2O	Short-term (year of the study) and long-term (not defined)	Mean national and regional values	Improved technology for production of ethanol in the long term	Btu/mile	Not specified	Not considered
Sheeran et al. [6]	1998	USA	Partial: LCI and interpretation	B100, B20 and diesel oil	1st level	Supply chain and final use	Energy, GHG, local atmospheric pollutants	Short-term (year of the study)	Mean national and international values	Usual technology on the study date	bhp-h	Mass equivalent	Not considered
International Energy Agency [3]	1999	EC	Partial: LCI	Gasoline, diesel oil, LPG, CNG, M100, E100, B100, HC, DME	1st level	Supply chain and final use	Energy, CO_2, NO_X, HCNM, MP	Short-term (1–5 years) and long tern (5–25 years)	Mean values of OECD countries.	Usual technology on the study date	GJ	Not specified	Not considered
Armstrong and Akhurst [7][1]	2000	EC	Not disclosed	Gasoline, diesel oil, LPG, CNG, M100, E100, B100, HC, electricity	1st level	Supply chain and final use	Energy, CO_2	Medium-term	Mean values of EC countries	Usual technology on the study date	MJ/km	Not specified	Not considered
Berr et al. [8]	2001	Australia	Complete: 4 phases of the LCA	Premium gasoline w/o sulfur, E85, E10, LPG, CNG, LNG, B100, diesohol, diesel oil and GTL diesel oil	1st level	Supply chain and final use	Energy, GHG and local atmospheric pollutants	Short-term	Mean national values	Usual technology on the study date	g/t km	Energy and mass equivalent	Not considered
Hackney and Neufville [9]	2001	USA	Partial: LCI	Gasoline, reformulated gasoline, diesel oil, M85, E85, M100, E100, LPG, CNG, LNG, HC, electricity	1st level	Supply chain and final use	Energy, CO_2, NO_X, HCNM, MP	Medium-term (12 years of vehicle lifetime)	Mean national values	Usual technology on the study date	Energy in 12 years of vehicle life	Mass equivalent	Not considered
Kadam [10]	2002	India	Complete: 4 phases of the LCA	E10	1st level	Supply chain and final use	Energy, CO2, CO, NO_X, SO_X, HC and MP	Short-term (year of the study)	Mean national values	Usual technology on the study date	1 metric ton of dry bagasse	Not specified	6 categories[3]
Kreith et al. [11]	2002	USA	Partial: LCI	CNG, HC, diesel oil GTL, M100, electricity	1st level	Supply chain and final use	Energy	Short-term (year of the study)	Mean national values	Usual technology on the study date	Not disclosed	Not specified	Not considered
Hu et al. [12]	2004	China	Partial: LCI	E85, gasolina	Not specified	Supply chain and final use	Energy, CO_2, CO, HC, NO_X, MP e custos	Short-term (year of the study)	Mean national and international values	Usual technology on the study date	200,000 km	Not specified	Not considered
Wang et al. [13]	2005	China	Partial: LCI	Metanol, gasolina e hidrogenio	Not specified	Supply chain and final use	Energy, CO_2, CO, HC, NO_X, MP, SO_X e custos	Short-term (year of the study)	Mean national and international values	Usual technology on the study date	200,000 km	Not specified	Not considered
Collela et al. [14]	2005	USA	Partial: LCI	Gasolina, oleo diesel, hidrogenio	1st and 2nd levels	Supply chain and final use	Energy, CO_2, CO, HC, NO_X, MP, SO_X, CH_4	Short-term (year of the study)	Mean national values	Usual technology on the study date	1 year operation	Not specified	Not considered

USA – United States; EC – European Community; MTBE – methyl *tert*-butyl ether; E*X* – blend with *X*% ethanol and 100-*X*% gasoline, M*X* – blend with *X*% methanol and 100-*X*% gasoline; B*X* – blend with *X*% biodiesel and 100-*X*% diesel oil; LPG – liquefied petroleum gas, CNG – compressed natural gas, LNG – liquefied natural gas; CH – compressed hydrogen; DME – dimethyl ether; GTL – gas to liquid. *Notes*: 1 – The work does not make clear what the stages of the supply chain are for each alternative, 2 – Consumption of fossil fuels, global warming, photochemical oxidants, acidification and generation of solid wastes, and 3 – Consumption of fossil fuel, global warming, acidification, eutrophization, human toxicity and malodorous air.

In this respect, it has become a common practice in developed countries to apply life cycle analysis (LCA), a technique that considers energy use and all other inputs and environmental impacts along the life cycle of various transportation energy sources (ES) [3].

Starting from an analysis of a set of selected references, a first approach life cycle inventory (LCI) procedure was draw up to evaluate total and renewable energy in Brazilian automotive fuels life cycle (LC). The amount of CO_2 emissions is also estimated from fossil fuel use. The procedure is used to compare three fuels – gasoline with 25% ethanol, pure ethanol and compressed natural gas – considering their final use in passenger car urban traffic in the municipality of Rio de Janeiro. An in-deep research was made to collect representative and unpublished data of Brazilian automotive fuels LC reality, in particular the 10 years time data base obtained from Petrobras (Brazilian Petroleum Company) for fossil fuels (gasoline and natural gas).

2. The LCI procedure

Based on selected bibliographical references, as shown in Table 1, a first approach LCI procedure was draw up as presented Fig. 1 that shows the procedure's scheme and serves as a basis for the discussion that follows.

2.1. Phase 1: Objective and scope

The objective divides into application of life cycles of transport energy sources, purpose being to evaluating fuel alternatives concerning total and renewable energy and CO_2 emissions amounts and function to produce movement in passenger car urban traffic.

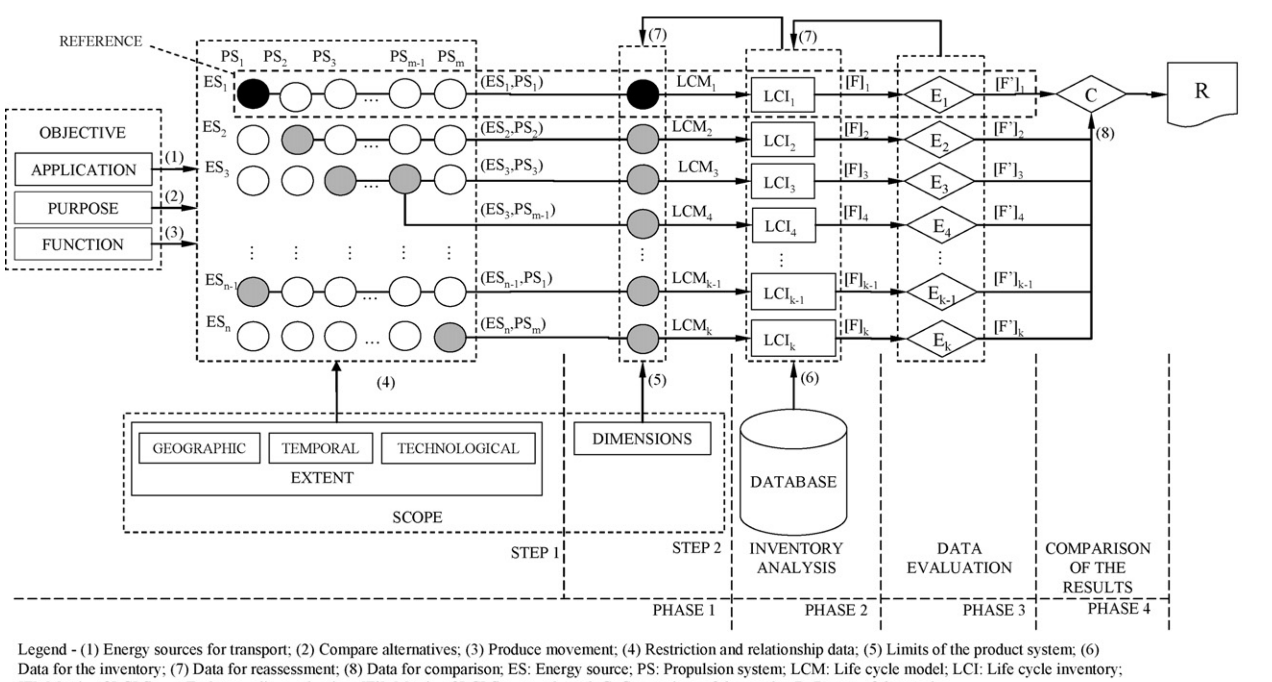
In Step 1 of the scope, the consideration of limits to the geographic, temporal and technological extent restricts and relates the ES, associated with the supply chains; and the propulsion systems (PS), associated with their final use. Each pair (ES, PS) must be characterized as specifically and in as much detail as necessary, considering that a PS can use more than one ES, that the mixture of two or more ES represents new supply chain, that different production processes lead to different supply chains and that the final use conditions must be specified, because they modify the performance of the propulsion systems.

In Step 2 of the scope, for each (ES, PS) pair, life cycle models (LCMs) are associated that establish the dimensions of the application and the flows to be considered. A modular structure for preparing the LCMs (Figs. 2 and 3), with three depth levels, in the form of macro-stages, meso-stages and micro-stages, permitting successive refinements and guaranteeing the equivalence among the levels, is recommended. Since the micro-stages are specific for each life cycle, it is recommended that the comparison of alternatives be done at the meso-stage level, where better equality can be achieved.

Regarding selected bibliographical references (Table 1), it is initially recommended considering level 1 (inputs and environmental loads directly associated with the processes). Refinements can be obtained considering level 2 (inputs and environmental loads for producing the level 1 inputs) and level 3 (inputs and environmental loads for producing level 2 inputs and capital goods). From the standpoint of energy consumption, it is common to consider for each process the total energy (TE), renewable energy and greenhouse gases (mainly CO_2 emissions) from fossil fuels.

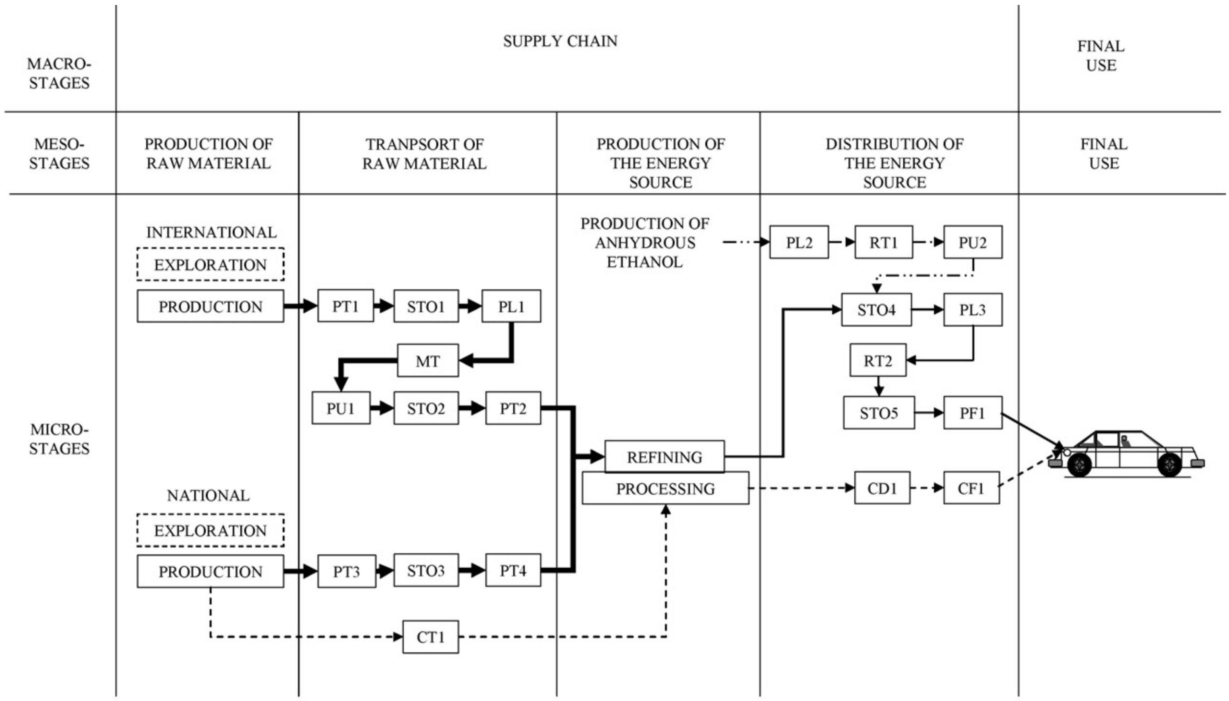
2.2. Phase 2: Analysis of the inventory

The data are then collected for each of the LCMs resulting from Phase 1, which is called life cycle inventory. In a preliminary study, the data about which there is little concern with quality are quantified. For some processes there will be very reliable data available in the form of historic series, permitting the consolidation of mean values and variation intervals as an expression of their consistency. For data obtained from general use databases, which



Legend - (1) Energy sources for transport; (2) Compare alternatives; (3) Produce movement; (4) Restriction and relationship data; (5) Limits of the product system; (6) Data for the inventory; (7) Data for reassessment; (8) Data for comparison; ES: Energy source; PS: Propulsion system; LCM: Life cycle model; LCI: Life cycle inventory; [F]: Matrix of LCI flows; E: data quality evaluation; [F']: Matrix of LCI flows evaluated; C: Comparison of the results; R: Report of the results.

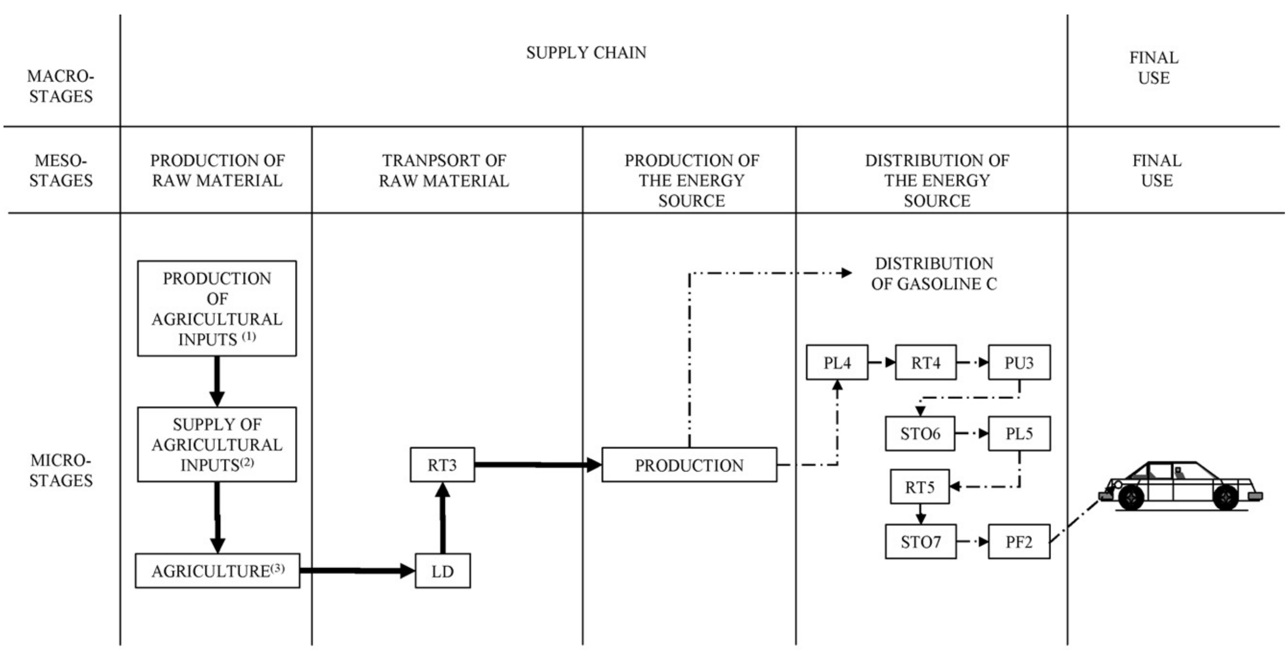
Fig. 1. Structure of the procedure.



Legend - Oil Gasoline A Gasoline C Ethanol Natural Gas

PF: pumping for fueling; PL: pumping for loading; PU: pumping for unloading; PT: pumping for pipeline transport; STO: storage; MT: maritime transport; RT: road transport; CT: compression for pipeline transport; CD: compression for piped distribution; CF: compression for fueling.

Fig. 2. Life cycle models (LCMs) for gasoline C (GC) and compressed natural gas (CNG).



Legend - sugarcane anhydrous ethanol hydrated ethanol

PF: pumping for fueling; PL: pumping for loading; PU: pumping for unloading; LD: loading; STO: storage; RT: road transport.
Notes - (1): Energy embodied in seedlings = 5.87 MJ/tc; fertilizers = 66.49 MJ/tc; lime = 7.14 MJ/tc; herbicides = 11.26 MJ/tc and insecticides = 0.79 MJ/tc (Nogueira, 1987; Centro de Tecnologia da Cana-de-açúcar, 2003); (2): Diesel oil for transporting seedlings, organic and chemical fertilizers equal 8.2 0.8 MJ/tc (Centro de Tecnologia da Cana-de-açúcar, 2003); (3): Soil preparation, planting and mechanized harvesting.

Fig. 3. Life cycle model (LCM) for hydrated ethanol (HE) and anhydrous ethanol (AE).

have less integrity and consistency, it is recommended adopting the upper limit of available data [15], accompanied by the pertinent justifications and comments.

As a result of Phase 2, each LCM is associated with a matrix [F] of flows per process, which will undergo evaluation of the data's quality in Phase 3.

2.3. Phase 3: Evaluation of the data

The evaluation criterion varies in function of the need of each study. For a preliminary approach it is recommended a criterion based on ref. [15], who propose evaluations regarding: (1) the weight that the individual inputs and environmental loads of each process have in relation to the respective total flows in the life cycle, (2) the variation interval of the values of each flow, and (3) the origin, which can be specific or general use.

It is recommended [15] that all the flows with weight (W) greater than 10% (W_{min} = 10%) should be assessed regarding the interval of variation and origin. Flows that present $W_{flow} \geq W_{min}$ and interval of variation (T) greater than a maximum (T_{max}) should be evaluated as to the origin of the data. If these flows have been determined from specific use data, excessive variation can reflect inconsistency. If they have been obtained from general use data, in which case they are called critical flows, it is recommended that their origin be reassessed and an effort be made to increase their integrity.

It is up to each analyst, according to the limitations of each case, to determine the depth to employ in reassessing the data. Placing priority on reappraising the data related to critical flows guides the efforts necessary to improve the LCI and permits establishing a process of progressive refinement, which reduces the time and costs of this operation. Phase 3 produces a matrix of flows [F'] evaluated by meso-stage for each alternative.

2.4. Phase 4: Comparison of the results

The comparison of the results can follow various criteria. For example, the values of [F'] for each alternative can be mutually compared or compared against a benchmark, furnishing a ranking, or parameterization of the alternatives outcomes, considering one alternative or the best results of each alternative as a reference.

3. Procedure's application – the case study of Rio de Janeiro municipality

The procedure was applied by choosing a typical, but not restrictive, situation: passenger car use in Brazil.

3.1. Phase 1: Objective and scope

It was selected as an application the life cycles of energy sources for transport by passenger car in order to compare alternatives, using as a function the movement of passengers (pass). Hence, the functional unit is 1 pass km.

3.1.1. Phase 1 – Step 1 – Extent

It was chosen as geographic extent urban traffic in the municipality of Rio de Janeiro, selecting ES alternatives for PS available in the current market, with legal, technological and economic feasibility and available data. Table 2 presents the results of Step 1 of the scope with characterization of the (ES, PS) pairs. This choice does not limit the procedure's application and is justified by the considerations presented next.

As in other Brazilian states, most cars in Rio de Janeiro use either gasoline blended with anhydrous ethanol (gasoline C) or pure hydrated ethanol (ethanol) as their exclusive fuels. However, since 2003, flexible-fuel cars have also been sold in Brazil that can use gasoline C and ethanol in any proportion [16]. It is prohibited for passenger cars, cargo vehicles and mixed-use vehicles rated at less than 1 metric ton, whether domestic or imported, to run on diesel in Brazil [17].

Between 1996 and 2005, passenger cars represented 89% of sales of vehicles consuming gasoline C and/or ethanol, including flex-fuel cars, which represent 53% of sales [16].

Vehicles of all three types (gasoline C, ethanol or flex-fuel) can be converted to run on CNG, assuming the bi-fuel configuration. This is a more recent trend, and in 2006 some 4% of Brazil's cars had this configuration. Rio de Janeiro was responsible for 42% of this fraction, giving it the country's largest fleet of cars running on vehicular natural gas (VNG) [18].

Passenger cars have various configurations of weight, power and engine displacement, all of which condition their fuel consumption. As can be seen in Table 2, the same representative vehicle configuration for each energy source was selected. This configuration reflects the typical characterization of flex-fuel vehicles.

The traffic regime and vehicle occupancy also cause fuel consumption to vary. Brazil is an increasingly urbanized country. In 2000, 81% of the population lived in cities [19]. In the city of Rio de Janeiro the use of cars for urban commuting in 2003 represented nearly 30% of the trips taken, growing 10% between 1994 and 2003 [20], justifying the operating profile presented in Table 2.

Table 2
Result of Step 1 of the procedure – characterization of the alternative pairs (ES, PS)

Energy source			Propulsion system[b]			Alternatives
Name	Initials	Characterization	Name	Initials	Characterization	
Gasoline C	GC	Blend of 75% gasoline refined from petroleum and 25%[a] anhydrous ethanol obtained from processing sugarcane	Conventional	PSC	Passenger car[c] running only on gasoline C	(GC, PSC)
Compressed natural gas	CNG	Natural gas associated with crude oil, purified and compressed	Bi-fuel	PSBF	Passenger car[c] running on gasoline C and adapted to use CNG[d]	(CNG, PSBF)
Hydrated ethanol	HE	Hydrated ethanol obtained from processing sugarcane	Flexible-fuel	PSFF	Passenger car[c] able to run on any blend of gasoline C and/or hydrated ethanol[e]	(HE, PSFF)

[a] Percentage in effect at the time of preparing the article, variable between 20% and 25% in function of government policy.
[b] Operating profile: urban traffic with average speed of 20 km/h, air conditioner on and average of 1.0 passengers per vehicle (PDT-RJ, 2006).
[c] Small car weighing 1450 kgf empty, equipped with a spark ignited internal combustion engine with 1.6 dm^3 displacement and 97 hp of maximum power, with manual transmission.
[d] Assumes it mainly uses CNG, although it can consume gasoline C.
[e] Considers that flex-fuel vehicles mainly use ethanol.

Table 3
Life cycle inventory of gasoline C

			Total energy (kJ/pass km)			Renewable energy (kJ/pass km)			CO_2 emissions (g/pass km)		
Meso-stages	Micro-stages	Origin of data	Mean	Variation	Weight	Mean	Variation	Weight	Mean	Variation	Weight
Production of raw material	Exploration	spec. use	15.46	12.42%	0.3932%	0.00	–	0.0000%	1.07	12.40%	0.583%
	Production	spec. use	127.80	12.08%	3.2389%	0.00	–	0.0000%	5.73	13.08%	3.139%
	Anhydrous ethanol portion	spec. use	37.84	6.02%	0.9044%	0.00	–	0.0000%	0.65	6.02%	0.332%
Transport of raw material	Pumped for transport (PT1)	gen. use	0.19	21.45%	0.0052%	0.00	–	0.0000%	0.01	21.45%	0.007%
	Pumped for loading (PL1)	gen. use	0.35	8.36%	0.0086%	0.00	–	0.0000%	0.03	8.36%	0.013%
	Maritime transport (MT)	spec. use	17.62	9.03%	0.4338%	0.00	–	0.0000%	1.28	9.03%	0.676%
	Pumped for unloading (PU1)	gen. use	0.35	8.36%	0.0086%	0.00	–	0.0000%	0.03	8.36%	0.013%
	Pumped for transport (PT2)	spec. use	0.44	16.06%	0.0116%	0.59	16.06%	0.0710%	0.00	0.00%	0.000%
	Storage at terminal (STO1 + STO2)	spec. use	0.24	19.07%	0.0066%	0.00	–	0.0000%	0.01	21.08%	0.008%
	Pumped for transport (PT3 + PT4)	spec. use	1.18	16.06%	0.0310%	1.57	16.06%	0.1898%	0.00	0.00%	0.000%
	Storage at terminal (STO3)	spec. use	0.24	19.07%	0.0066%	0.00	–	0.0000%	0.01	21.08%	0.008%
	Anhydrous ethanol portion	spec. use	11.91	11.69%	0.3008%	0.00	–	0.0000%	0.78	6.02%	0.401%
Production of the energy source	Refining	spec. use	240.95	11.04%	6.0467%	1.75	11.04%	0.2018%	16.78	11.04%	9.02%
	Anhydrous ethanol portion	spec. use	281.13	6.02%	6.7190%	281.13	**11.30%**	**30.89%**	0.00	–	0.0000%
Distribution of the energy source	Storage at the base (STO4)	NC	–	–	–	–	–	–	–	–	–
	Pumping for loading (PL3)	spec. use	0.16	12.04%	0.0040%	0.16	12.04%	0.0184%	0.00	0.00%	0.0000%
	Road transport (RT2)	spec. use	2.69	24.25%	0.0770%	0.00	–	0.0000%	0.19	24.25%	0.1150%
	Storage at the service station (STO5)	NC	–	–	–	–	–	–	–	–	–
	Pumping for fueling (PF1)	spec. use	0.06	6.02%	0.0013%	0.06	6.02%	0.0062%	0.00	0.00%	0.0000%
	Anhydrous ethanol portion (PL2 + RT1 + PU2)	spec. use	11.19	22.12%	0.3146%	0.09	6.02%	0.0102%	0.66	6.02%	0.3390%
Supply chain total		–	749.80	9.30%	18.512%	285.34	6.13%	31.387%	27.23	11.14%	14.658%
Final use		spec. use	3.409,50	**6.02%**	**81.488%**	624.43	**6.02%**	**68.613%**	166.67	**6.02%**	**85.342%**
Life cycle total		–	4.159,30	6.61%	100.00%	909.77	6.06%	100.00%	193.90	6.74%	100.00%

Bold values: $W_{flow} \geq W_{min}$ and $T_{flow} > T_{max}$; NC: flow not considered in the data inventory; spec. use: specific use datum; general use datum; –: value not considered, PF: pumping for fueling; PL: pumping for loading; PU: pumping for unloading; PT: pumping for pipeline transport; STO: storage; MT: maritime transport; RT: road transport.

Table 4
Life cycle inventory of compressed natural gas

Meso-stages	Micro-stages	Origin of the data	Total energy (kJ/pass km)			Renewable energy (kJ/pass km)			CO_2 emissions (g/pass km)		
			Mean	Variation	Weight	Mean	Variation	Weight	Mean	Variation	Weight
Production of raw material	Exploration	NC	–	–	–	–	–	–	–	–	–
	Production	spec. use	165.09	11.02%	4.1460%	0.00	–	0.000%	7.36	11.02%	3.793%
Transport of raw material	Compression for transport (CT1)	spec. use	2.50	7.01%	0.0605%	2.50	7.01%	2.659%	0.00	–	0.000%
Production of raw material	Processing	spec. use	41.93	9.01%	1.0332%	0.00	–	0.000%	1.73	4.01%	0.833%
Distribution of the energy source	Compression for distribution (CD1)	gen. use	2.50	7.01%	0.0605%	2.50	7.01%	2.659%	0.00	–	0.000%
	Compression for fueling (CF1)	spec. use	84.09	13.19%	2.155%	84.09	**13.19%**	**94.68%**	0.00	–	0.000%
Supply chain total		–	296.12	11.28%	7.455%	89.10	12.85%	100.00%	9.09	9.68%	4.626%
Final use		spec. use	3,943.02	4.01%	92.54%	0.00	0.00%	0.000%	198.09	4.01%	95.37%
Life cycle total		–	4,239.13	4.51%	100.00%	89.10	12.85%	100.00%	207.18	4.26%	100.00%

Bold values: $W_{flow} \geq W_{min}$ and $T_{flow} > T_{max}$; NC: flow not considered in the data inventory; spec. use: specific use datum; gen. use: general use datum; –: value not considered. CT: compression for pipeline transport; CD: compression for piped distribution; CA: compression for fueling.

3.1.2. Phase 1 – Step 2 – Dimensions

Figs. 2 and 3 present the LCMs adopted for the alternatives on Table 2. Since the natural gas (NG) used in Brazil is extracted in association with petroleum, it was represented in the same LCM of gasoline C. For each micro-stage it was considered the flows of total energy, renewable energy and net emission of carbon dioxide (CO_2), defined as the gas emitted by burning fossil fuel.

Half of the oil processed to supply the city of Rio de Janeiro (about 7×10^6 m^3) comes from onshore fields in the Middle East and the rest from fields offshore of the state of Rio de Janeiro [21,22].

Table 5
Life cycle inventory of hydrated ethanol

Meso-stages	Micro-stages	Origin of the data	Energy total (kJ/pass km)			Renewable energy (kJ/pass km)			CO_2 emissions (g/pass km)		
			Mean	Variation	Weight	Mean	Variation	Weight	Mean	Variation	Weight
Production of raw material	Production of agricultural inputs[a]	spec. use	195.91	5.01%	3.012%	–	–	–	–	–	–
	Supply of agricultural inputs[b]	spec. use	17.54	16.97%	0.297%	0.00	–	0.000%	1.22	16.97%	7.370%
	Agriculture[c]	spec. use	53.70	14.04%	0.900%	0.00	–	0.000%	3.74	**14.04%**	**22.34%**
Transport of raw material	Loading (LD)	spec. use	13.24	14.04%	0.222%	0.00	–	0.000%	0.92	14.04%	5.510%
	Road transport (RT3)	spec. use	68.56	10.03%	1.107%	0.00	–	0.000%	4.78	**10.03%**	**27.47%**
Production of the energy source	Production	spec. use	1,930.63	**10.08%**	**29.69%**	1,930.63	**10.08%**	**31.93%**	0.00	–	0.000%
Distribution of the energy source	Pumping for loading and unloading (PL4 + PU3)	spec. use	0.68	11.03%	0.011%	0.68	11.03%	0.012%	0.00	–	0.000%
	Road transport (RT4)	spec. use	76.14	21.17%	1.379%	0.00	–	0.000%	5.30	**21.17%**	**34.22%**
	Storage at the base (STO6)	NC	–	–	–	–	–	–	–	–	–
	Loading (LD5)	spec. use	0.34	11.03%	0.006%	0.34	11.03%	0.006%	0.00	–	0.000%
	Road transport (RT5)	spec. use	6.73	23.21%	0.006%	0.00	–	0.000%	0.47	23.21%	3.081%
	Storage at the service station (STO5)	NC	–	–	–	–	–	–	–	–	–
	Pumping for fueling (PF2)	spec. use	0.12	5.01%	0.002%	0.12	5.01%	0.002%	0.00	–	0.000%
Supply chain total		–	2,363.58	6.08%	36.75%	1,931.76	5.02%	31.95%	16.43	15.65%	100.00%
Final use		spec. use	4,113.67	5.00%	63.25%	4,113.67	5.00%	**68.05%**	0.00	0.00%	0.000%
Life cycle total		–	6,477.26	5.40%	100.00%	6,045.43	5.01%	100.00%	16.43	15.65%	100.00%

Bold values: $W_{flow} \geq W_{min}$ and $T_{flow} > T_{max}$; NC: flow not considered in the data inventory; spec. use: specific use datum; gen. use: general use datum; –: value not considered; PF: pumping for fueling; PL: pumping for loading; PU: pumping for unloading; LD: loading; STO: storage; RT: road transport.

[a] Seedlings, organic and chemical fertilizers, lime, herbicides, insecticides.

[b] Seedlings, organic and chemical fertilizers.

[c] Soil preparation, planting and mechanized harvesting.

It is assumed that seaborne transport of imported oil over 8,746 ± 262 nautical miles [23] in ships of 300,000 DWT, transport from well to terminal in the Middle East of 145 ± 15 km in pipelines [24] and from terminal to refinery in Brazil in a pipeline of 125 km. Transport of domestic crude oil is exclusively through a pipeline of 334 km [25]. In national refineries, the oil is kept warm to facilitate pumping [26].

After refining, gasoline A (without admixture of ethanol) is pumped through pipes to tanks near the refinery, where 25% anhydrous ethanol is blended in, producing gasoline C. This is carried in tank trucks holding 30,000 l, which distribute it to service stations over an average distance of de 26.23 ± 1.84 km [27,28].

The natural gas associated with domestic crude oil can be reinjected in the well, flared off, consumed on the platforms or sent to be marketed [21,26]. The gas to be sold is carried in pipelines over a distance of 452 km to the processing unit [25]. After processing, it is distributed through a network of 638 km of pipes to the service stations [29], where it is compressed to 220 atm to fuel the vehicles.

It is assumed that all the ethanol consumed in the municipality of Rio de Janeiro is produced in São Paulo state and carried in tank trucks holding 30,000 l over a route averaging 697 ± 24 km until the distribution base in Rio de Janeiro [27,28,30]. From this point it follows the distribution model of gasoline C.

The raw material to produce ethanol is sugarcane, harvested and ready for loading onto 23-ton trucks, which carry it 20 ± 5 km to the distilleries. We assume 25% is harvested mechanically and the rest by hand, with mechanized loading [28].

3.2. Phase 2: Analysis of the inventory

Tables 3–5 show the results of the life cycle inventory for gasoline C (GC), hydrated ethanol (HE) and CNG, based on the LCMs presented in Figs. 2 and 3 (used to support the following discussion).

Inferior calorific power (ICP) was chosen for calculation of the energy content of the fuels. The embodied energy was disregarded, because its identification is one of the work's objectives.

The net CO_2 emissions (E_{CO_2}) were calculated using Eq. (1) applied to fossil fuels (fuel oil, diesel oil, natural gas, refinery gas, coke and gasoline A). It is assumed that the CO_2 emitted by fuels from biomass (sugarcane straw and bagasse and ethanol) is reabsorbed in producing raw material and disregarded the CO_2 emitted in generating hydroelectricity because it is considered a second-level flow [31].

$$E_{CO_2} = EC_F F_{con} F_{corr} F_{ox} F_{CO_2} \quad (1)$$

where: EC_F – energy content of the fuel (MJ/t); F_{con} – conversion factor (tC/MJ); F_{corr} – correction factor from SCP to ICP (0.90 – gases and 0.95 – liquids); F_{ox} – carbon dioxide proportion factor (0.995 – gases and 0.99 – liquids); F_{CO_2} – conversion factor of C to CO_2 (3.67).

From the energy consumption historic series [26], the arithmetic means was obtained and standard deviation and Student's t distribution coefficients at a 90% level of significance for the estimate of the variation [32] was used. For data available in the form of intervals, it was determined the interval center (mean value) and the variation by its amplitude divided by two.

Figures on natural gas consumed in producing domestic oil and NG itself were obtained from the annual inventories conducted between 1990 and 2003 [26]. As an allocation criterion the mass ratio was used (0.043 kg of NG to 1 kg of oil). The diesel oil consumed in exploration and the NG reinjected were allocated exclusively to petroleum, because their purpose is to obtain it [26]. For petroleum, the values obtained were: 0.0042 ± 0.0005 tEP/t (exploration) and 154 ± 11 MJ/barrel (production), and for NG, 2004 ± 140 MJ/t (production).

For imported oil, it was adopted 0.0075 ± 0.0004 tEP/t for onshore exploration and 97 ± 5 MJ/barrel for production in the Persian Gulf. It was also assumed the use of diesel oil in exploration and NG in production [6].

Pumping of domestic oil for transport (PT2, PT3 and PT4) consumes 0.0311 ± 0.0031 kWh/t km of electricity and (1.79 ± 0.23) 10^{-4} tEP/t for heating at the terminals (STO2 and STO3), using fuel oil and NG [26]. It was assumed 0.0144 ± 0.0007 kWh/t km of NG for pumping in the Middle East (PT1) [6] and the national figure for heating at the terminal STO1.

For maritime transport (MT), it was assumed consumption between 1.543 and 1.637 g/t nautical mile of fuel oil for tanker capacity range from 328,000 to 347,000 m^3. Pumping for loading and unloading (PL1 and PU1, respectively) consume between 3.7 and 3.5 t/h of fuel oil [25,33].

The historic series (1990–2003) for consumption of fuel oil, NG, refinery gas, coke and electricity for refining crude oil and processing NG were obtained from [26]. For the period from 1999 to 2003 the production of gasoline A and other refined products were obtained from ref. [21], allowing it to calculate the energy efficiency of the process (89–91%) and the mass and energy balances (6–8%). The electricity and NG consumed were divided by the mass of the petroleum derivatives and dry NG produced. The other fuels consumed in the refinery only were divided by the petroleum derivatives [26]. The values obtained were 3798 ± 190 MJ/t (gasoline A) and 509 ± 25 MJ/t (NG).

Loading on trucks for distribution of gasoline C (PL3) consumes 2.32 ± 0.17 MJ/t of electricity [26,34]. The typical energy efficiency values for 30,000-l tank trucks (RT1 and RT2) vary between 1.81 and 2.25 km/l [35], and it was used 0.654 ± 0.033 MJ/m^3 as the electricity consumption for pumping to fuel cars (PF1) [36]. Storage at the base (STO4 and STO6) and service stations (STO5 and STO7) does not consume energy and the emissions from evaporation were not part of the scope of this work.

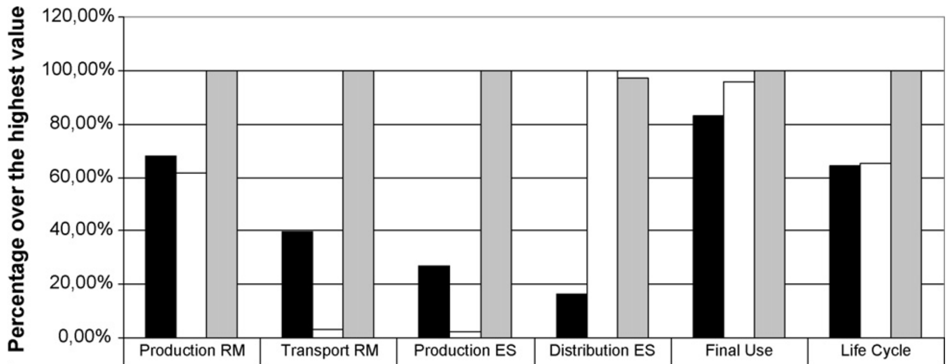
The data on electricity consumed in transporting NG for processing (CT1) was obtained from [26] from the historic series (1990–2003), with a figure of 30 ± 0.9 MJ/t. This same value was used as a conservative estimate for distribution of NG (CD1), because of the difficulty of obtaining specific data. For compression of NG for fueling (CF1), it was used 1021 ± 94 MJ/t [26].

In the ethanol supply chain it was assumed 65 t_c/ha (t_c/ha = metric ton of cane per hectare) for production of sugarcane and 85.4 l/t_c for production of ethanol [28,37,38].

For coherence with the works presented in Table 1, it was considered the embodied energy in the agricultural inputs and their supply, although these are second-level flows. The sugarcane growing cycle lasts 5 years, with planting (1 time), regrowth from stumps (3 times) and mechanized harvesting (4 times), using equipment that consumes diesel oil and total 25.10 ± 2.25 MJ/t_c [28,37]. The consumption of energy to produce raw material totaled 1807 ± 45 MJ/t_{HE} (t_{HE} = metric ton of hydrated ethanol).

The loading (LD) and road transport (RT3) of sugarcane to the distilleries uses loaders and trucks that consume diesel oil at rates of 16.25 ± 1.62 l/ha and 0.0209 to 0.0231 l/t km, respectively [38]. The consumption of energy for transport of raw material totaled 553 ± 31 MJ/t_{HE}.

It was assumed that all the energy necessary to produce ethanol (crushing, fermentation, distillation and generation of electricity) is obtained from burning 232 kg/t_c of bagasse with ICP of 1650 kcal/kg and efficiency in conversion into steam of 78%,



	Production RM	Transport RM	Production ES	Distribution ES	Final Use	Life Cycle
■ (GC,PSC)	67,79%	39,77%	27,04%	16,27%	82,88%	64,21%
□ (CGN,PSBF)	61,80%	3,06%	2,17%	100,00%	95,85%	65,45%
▨ (HE,PSFF)	100,00%	100,00%	100,00%	97,00%	100,00%	100,00%

Legend – RM: raw material; ES: energy source.
Note: Alternatives (GC, PSC), (CNG, PSBF) and (HE, PSFF) are as defined in Table 2.

Fig. 4. Total energy consumed in each alternative.

producing an 8% excess of bagasse, which is considered as a co-product due to its potential to generate marketable electricity [39]. It was obtained 58% energy efficiency for the process, 7% for the mass balance, 0.3% for the energy balance and 13,355 ± 668 MJ/t_{HE}.

By analogy with the calculations used for gasoline C, it was obtained 519.6 ± 92 MJ/t_{HE} for loading and unloading (PL4 and PU3) and road transport from the distillery to the distribution base (RT4) and 48.6 ± 9 MJ/tHE for urban distribution (PL5 and RT5) and fueling (PF2).

For each propulsion system presented in Table 2, it was collected field efficiency data for three vehicles with the characteristics and operating profile described in notes (2) and (3) [28,40]. A conservative position applied, choosing the lowest figures for each alternative, which were: 8.76 ± 0.52 km/l for (GC, PSC); 9.47 ± 0.38 km/m^3 for (CNG, PSBF) and 5.47 ± 0.27 km/l for (HE, PSFF).

3.3. Phase 3: Evaluation of the data

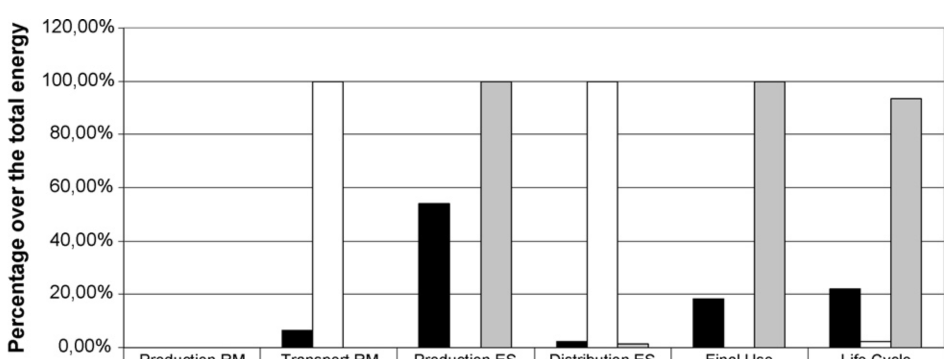
The purpose of this phase is to orient a possible reassessment of the data by identifying critical flows. The parameters we adopted were: W_{mim} = 10% and T_{max} = 5% [15].

From Tables 3–5, a total of 14 flows stand out with $W_{flow} \geq 10\%$, of which 10 present $T_{flow} > 5\%$, none involving general use data, not being considered critical. The main aspect to be evaluated in this case is the consistency of the data.

The variations relative to the final use flows for the alternative (GC, PSC) surpassed T_{max} by 1.022%, associated with the results of the field study of the energy efficiency of the cars chosen. It was tested the consistency of the results by comparing them with bibliographical reference data that reflect Brazilian reality [41,42,43].

A limitation of this phase of the work refers to the consistency test of the flow of compression of NG for fueling. It was managed to obtain references for the mean values [44–46], but not for their variation. Other limitations were the consistency test of the net CO_2 emissions flows in agriculture and transport of sugarcane (RT3) and transport of ethanol (RT1 and RT4), total energy and renewable energy in producing ethanol and the impacts of the portion of anhydrous ethanol in the renewable energy flow of gasoline C.

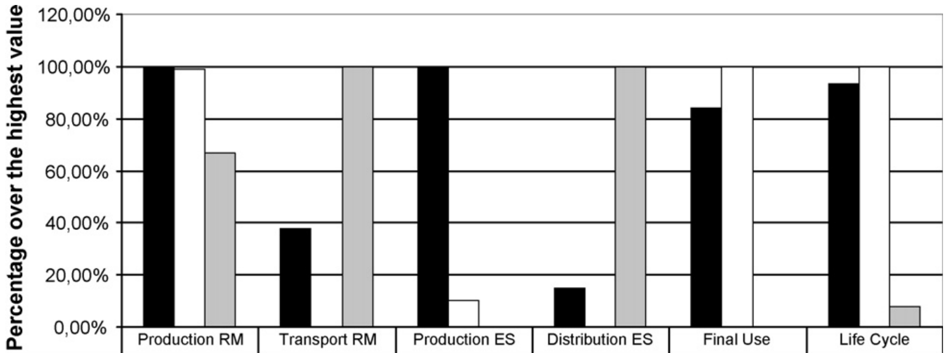
In all these cases, since they involved flows related to specific use data, it was chosen to maintain them.



	Production RM	Transport RM	Production ES	Distribution ES	Final Use	Life Cycle
■ (GC,PSC)	0,00%	6,63%	54,18%	2,18%	18,31%	21,87%
□ (CGN,PSBF)	0,00%	100,00%	0,00%	100,00%	0,00%	2,10%
▨ (HE,PSFF)	0,00%	0,00%	100,00%	1,35%	100,00%	93,33%

Legend – RM: raw material; ES: energy source.
Note: Alternatives (GC, PSC), (CNG, PSBF) and (HE, PSFF) are as defined in Table 2.

Fig. 5. Renewable energy associated with each alternative.



	Production RM	Transport RM	Production ES	Distribution ES	Final Use	Life Cycle
■ (GC,PSC)	100,00%	37,83%	100,00%	14,71%	84,14%	93,59%
□ (CGN,PSBF)	98,87%	0,00%	10,31%	0,00%	100,00%	100,00%
▨ (HE,PSFF)	66,65%	100,00%	0,00%	100,00%	0,00%	7,93%

Legend – RM: raw material; ES: energy source.
Note: Alternatives (GC, PSC), (CNG, PSBF) and (HE, PSFF) are as defined in Table 2.

Fig. 6. Net CO_2 emissions associated with each alternative.

3.4. Phase 4: Comparison of the results and discussion

To make visualization of the results easier, parametric comparison was chosen to display the procedure's outcomes. For each alternative in Table 2, the total energy consumption and net CO_2 emissions consider the highest value of each meso-stage as a reference. The consumption of renewable energy considers the total energy consumption as reference. Figs. 4–6, prepared from Tables 3–5, which present the absolute values, will serve as the base for discussing the results.

With the exception of distribution of the energy source, the alternative (HE, PSFF) presents the highest total energy consumption per meso-stage. The energy embodied in the agricultural inputs is the decisive factor making the total energy consumption for production of raw material for alternative (HE, PSFF) 32% greater than for alternative (GC, PSC) and 38% higher than for alternative (CNG, PSBF), with this last figure helped by the allocation criterion of not considering the diesel oil consumed in exploration for the associated NG.

In none of the alternatives consumption of renewable energy for production of raw material was found, which implies net CO_2 emissions roughly proportional to the total energy consumption for alternatives (GC, PSC) and (CNG, PSBF). The same does not occur with (HE, PSFF), where the net CO_2 emissions are associated only with the micro-stages of supply of agricultural inputs and agriculture itself.

The difference between total energy consumption for the transport of raw material for each alternative is a function of the type of transport and the criterion for allocating mass in converting the raw material into an energy source. Natural gas is carried by gas pipelines, petroleum is carried by oil pipelines and tankers, all of which are more energy efficient than roadway transport, used for sugarcane. Additionally, it was assumed that a small fraction of the sugarcane mass, equivalent to 85.4 l/t_c, is transformed into ethanol, while for oil and NG, except for small processing losses, all the raw material is transformed into marketable co-products.

Besides having the lowest total energy consumption, transport of NG uses exclusively renewable energy (hydroelectricity) and by hypothesis does not present net CO_2 emissions. This does not occur for the (GC, PSC) alternative, where only a small part of the total energy is renewable, and for the (HE, PSFF) alternative, where the energy consumed is of fossil origin (diesel oil), producing net CO_2 emissions with a profile similar to the consumption of total energy.

The total energy consumption to produce ethanol is 3.7 times greater than for gasoline C and 46 times greater than for NG, but all the energy consumed is from biomass (sugarcane bagasse), which means there are no net CO_2 emissions. The greatest part of the renewable energy observed to produce gasoline C (99%) comes from the addition of ethanol and the rest from the use of hydroelectricity.

Processing of NG consumes little total energy even when compared to production of gasoline C. The reason is the hypotheses adopted in the NG processing model, associated with the refining of oil, with a small part of the energy and net CO_2 emissions allocated to NG.

The biggest consumption of total energy for distribution per energy source occurs for (CNG, PSBF) and is associated with the electricity used to compress it for fueling cars. The use of diesel oil in road transport from distillery facilities to distribution bases implies higher net CO_2 emissions for ethanol in this meso-stage. For distribution of gasoline C, the total energy and net CO_2 emission represent, respectively, 16% and 15% of those obtained for ethanol. This difference is associated with the local transport of ethanol to the distribution base, since from this point on the distribution model is identical for the two alternatives.

The consumptions of total energy for transporting raw material and distributing the energy source for the (HE, PSFF) alternative present values of the same order, although the last meso-stage considers the movement to be much longer. This is another reflection of the mass relation between sugarcane and ethanol, which only becomes clear when considering the entire supply chain.

The (GC, PSC) alternative presents the best performance for final use, with total energy consumption 13.5% lower than for (CNG, PSBF) and 17% lower than for (HE, PSFF). For this last alternative, the net CO_2 emissions are nil, because it comes from biomass. The portion of ethanol added to gasoline C helps reduce its net CO_2 emission in final use, which does not occur for CNG, responsible for the highest net CO_2 emission at this meso-stage.

The portion of ethanol in gasoline C represents 38% of the renewable energy in the total supply chain of the (GC, PSC) alternative, a higher percentage than the 18.31% obtained for final use and 21.87% obtained for the life cycle. This finding is only possible through life cycle analysis.

The (GC, PSC) alternative shows the lowest total energy consumption for the life cycle, with similar performance to that of (CNG, PSBF) and 36% better than (HE, PSFF). However, the last

alternative has the advantage of using renewable energy (93%) and producing less net CO_2 emissions.

From a standpoint of total energy consumption, the best alternative would be (GC, PSC), followed by (CNG, PSCBC). However, the following aspects must be considered: (i) the fraction of ethanol in gasoline C represents an important renewable energy portion in its entire life cycle, something that does not occur for NG, and (ii) the life cycle model established for NG associated with petroleum privileges this alternative regarding total energy consumption and the uncertainties in the data on distribution of NG may have led to underestimating the energy consumption for this meso-stage. The last two items represent opportunities to improve on the present study.

From a perspective of renewable energy and net CO_2 emissions, the use of ethanol is unbeatable. Although it has undergone successive improvements in the raw material production and energy source meso-stages, this alternative still has opportunities for significant improvements in the raw material transport and energy source distribution meso-stages, indicating areas for future studies.

The results obtained represent Brazilian reality limited by the extent of the model. This situation benefits the (GC, PSC) and (CNG, PSBF) alternatives because of the proximity of the place of raw material production, in whole or in part, and the place of final use. These results should not be taken as national averages, which would require a different geographic extent for the models.

For the (GC, PSC) and (CNG, PSBF) alternatives, the supply chain consumes, respectively, 18% and 7% of the total energy of the life cycle. These figures are comparable with those obtained by ref. [3], namely 13–21% for gasoline and 6–13.5% for NG. In the case of the (HE, PSFF) alternative, the supply chain is responsible for 36.5% of the total energy of the life cycle, well under the 50.5–92% presented by [3]. However, in that study the ethanol considered was produced from corn and beets.

4. Conclusions and recommendations

The procedure presented here adheres to the LCI technique and is aligned with the practice presented in the standard and in the literature consulted (Table 1). The adoption of three levels of depth in preparing the life cycle models, in the form of macro-stages, meso-stages and micro-stages, permits making successive refinements, ensuring equivalence among the levels when comparing outcomes for different fuel alternatives.

The application of this procedure ratified its adequacy and represents an important contribution to the development and dissemination of knowledge on the life cycle of transportation energy sources in developing countries, since it considers data representative of a part of Brazilian reality. The data presented for the (GC, PSC) and (CNG, PSBF) alternatives and their comparison with data on the (HE, PSFF) alternative make this study groundbreaking.

Regarding the use of energy, total and/or renewable, the identification of the best energy source for passenger cars depends on which aspects are valued most. Strictly from a standpoint of lower total energy consumption, respecting the case study extent, the use of gasoline C and CNG, in that order, are the best alternatives. However, from a perspective of use of renewable energy and net CO_2 emissions ethanol is unbeatable.

Despite its privileged dimensional situation of CNG, which minimizes the total consumption of energy in the supply chain, the (GC, PSC) alternative performs better from a perspective of total energy use, besides having a significant portion of renewable energy through the addition of ethanol.

The results also show the procedure is suitable to identify where specific advantages occur along the life cycle of each alternative, in particular the use of renewable fuels made from biomass, an option already widely used in Brazil.

References

[1] Ministério de Minas e Energia (2007) Balanço Energético Nacional/BEN 2006. In www.mme.gov.br (accessed on February 7, 2007).

[2] D'Agosto MA, Ribeiro SK. Performance evaluation of hybrid-drive buses and potential fuel savings in Brazilian urban transit. Transportation 2004;31: 479–96.

[3] International Energy Agency (1999) *Automotive Fuels for the Future. The Search for Alternative*. Office of Energy Efficiency Technology and R&D, Paris.

[4] Furuholt E. Life cycle assessment of gasoline and diesel. Resources Conservation and Recycling 1995;14:251–63.

[5] Wang M, Sariks C, Wu M. Fuel-cycle fossil energy use and greenhouse gas emissions of fuel ethanol produced from U.S. midwest corn. Illinois: Centre of Transportation Research, Argone Laboratory; 1997.

[6] Sheehan J, Camobreco V, Duffiled J, Graboski M, Shapouri H. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. Final Report. National Renewable Energy Laboratory, Golden, Colorado, 1998.

[7] Armstrong AP, Akhurst MA. Alternative fuels: well-to-wheels energy use & CO_2 comparisons. Report of BP Amoco Search Group, London, 2000.

[8] Beer T, Grant T, Morgan G, Lapszewicz J, Anyon P, Edwards J. et al. Comparison of Transport Fuels: Life Cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles. Final Report EV45A/2/F3C, Australian Greenhouse Office, Sydney, 2001.

[9] Hackney J, Neufville R. Life cycle of alternative fuel vehicles: emissions, energy and cost trade-offs. Transportation Research Part A 2001;35:243–66.

[10] Kadam KL. Environmental benefits on a life cycle basis of using bagasse-derived ethanol as a gasoline oxygenate in India. Energy Policy 2002;30: 371–84.

[11] Kreith F, West RE, e Isler BE. Legislative and technical perspective for advanced ground transportation systems. Transportation Quarterly 2002;56:51–73.

[12] Hu Z, Pu G, Fang F, Wang C. Economics, environment, and energy life cycle assessment of automobiles fueled by bio-ethanol blends in China. Renewable Energy 2004;29:2183–92.

[13] Wang C, Zhou S, Hong X, Qiu T, Wang S. A comprehensive comparison of fuel options for fuel cell vehicles in China. Fuel Processing Technology 2005;86:831–45.

[14] Collela WG, Jacobson MG, Golden DM. Switching to a U.S. hydrogen fuel cell vehicle fleet: the resultant change in emissions, energy use, and greenhouse gases. Journal of Power Sources 2005;150:150–81.

[15] Maurice B, Frischknecht R, Coelho-schwirtz V, Hungerbühler K. Uncertainty analysis in the life cycle inventory. Application to the production of electricity with French coal power plants. Journal of Cleaner Production 2000;8:95–108.

[16] Associação Nacional dos Fabricantes de Veículos Automotores (2006) Anuário da Indústria Automobilística Brasileira. In www.anfavea.com.br/anuario2006/Cap02 (accessed on February 8, 2007).

[17] Departamento Nacional de Combustíveis (1994) Portaria 23 de 07/06/1994, Brasília, DF.

[18] Gasnet (2007) Perfil do VNG no Brasil. In www.gasnet.com.br/novo_gnv/perfilgnv/brasil_asp (accessed on February 9, 2007).

[19] Instituto Brasileiro de Geografia e Estatística (2006) Senso Demográfico de 2000. In http://www.ibge.gov.br/home/estatistica/populacao (accessed on July 4, 2006).

[20] Secretaria Municipal de Transportes do Rio de Janeiro (2006) Plano Diretor de Transportes da Cidade do Rio de Janeiro, Rio de Janeiro, RJ.

[21] Agência Nacional do Petróleo (2003) Anuário Estatístico da Indústria Brasileira do Petróleo 1993/2002, Rio de Janeiro, RJ.

[22] Medeiros A. Refino no Brasil. In *Cadernos Petrobras 3*. Petróleo Brasileiro S.A., Unidade de Comunicação Institucional da Petrobras, Rio de Janeiro, RJ, 2003.

[23] Dobson H, Bersford A. Maritime atlas of words ports and shipping places. London: Lloyd's of London Press Ltd.; 1989.

[24] Rio Oil & Gas (2002) Strategies for World Energy. In *Official publication of the 17th World Petroleum Congress*, pp. 158–59, Rio de Janeiro, RJ.

[25] Transpetro (2002) Relatório Anual 2001. Petróleo Brasileiro S.A., Transpetro, Rio de Janeiro, RJ.

[26] Petrobras (2003) *Relatório sobre conservação de energia no sistema Petrobras*. Petróleo Brasileiro S.A., CONPET, Rio de Janeiro, RJ.

[27] Menezes HL (2004) Procedimentos de operação no Núcleo de Caxias da Companhia Brasileira de Petróleo Ipiranga. Personal communication. Chief Enginner of Companhia Brasileira de Petróleo Ipiranga Fuel Distribution Base, Duque de Caxias, RJ.

[28] ÐAgosto MA (2004). Analysis of energy chain efficiency for the main energy sources used in roadway vehicles in Brazil. Doctor of Science (D.Sc.) thesis COPPE/UFRJ, Rio de Janeiro, Brazil.

[29] Secretaria de Energia, da Indústria Naval e do Petróleo (2000) Balanço Energético do Estado do Rio de Janeiro 1980/1999, Rio de Janeiro, RJ.

[30] Usinas e Destilarias do Oeste Paulista (2004) Acompanhamento da produção de álcool – Safra 00/01. In www.udop.com.br, Boletim II/NNE de 25/10, NO e CSUL de 17/10/00 (accessed on September 12, 2004).

[31] Ministério da Ciência e Tecnologia (2002) Primeiro inventário brasileiro de emissões antrópicas de gases de efeito estufa. Emissões de dióxido de carbono por queima de combustíveis: abordagem top-down, Brasília, DF.

[32] King LE. Statistical analyses. In manual of transportation engineering studies – appendix C. Prentice Hall Inc.; 1994. pp. 392–412.
[33] Gabina F. de C. Dados sobre a frota de petroleiro da Transpetro e sua operação. Personal communication. Maritime Engineer, Frota Nacional de Petroleiros, GETEC, Rio de Janeiro, RJ, 2004.
[34] Marques PSV. Tabela de consumo de energia nas bases da Companhia Brasileira de Petróleo Ipiranga. Personal communication. Chief Engineer, Seção de Bases e Terminais, Rio de Janeiro, RJ, 2003.
[35] Volvo. Estimativa de Custos de Transportes. São Paulo, SP: Volvo do Brasil S.A.; 2000.
[36] Gilbarco (2004) Linha de produtos Gilbarco, In www.gilbarco.com.br (accessed on September 28, 2004).
[37] Lima, L da R, Marcondes A de A. *Álcool carburante. Uma estratégia brasileira*, Ed. Da UFPR, 1ª ed., Curitiba, PR, 2002.
[38] Centro de Tecnologia da Cana-de-açúcar. Use of energy in the production of cane, sugar and alcohol and green house gas emissions: present situation (2002) and future situations (cogeneration with BIG-GT), Piracicaba, SP, 2003.
[39] Coelho ST, Oliveira Jr S, Zylbersztajn D. Thermo economic analysis of electricity cogeneration from sugarcane origin. Report of the Third Biomass Conference of the Americas, vol. II, pp. 1631–40, Montreal, 1997.
[40] Gomes R. Dados da frota da empresa Veloz Transrio que operação no Aeroporto Santos Dumont no período de outubro de 2003 a maio de 2004. Personal commuication. Veloz Transrio Ltda, Rio de Janeiro, RJ: Manager of the Company; 2004.
[41] Clauset C. (1999) Gol 1.6 de cara nova. Revista Quatro Rodas, May, pp. 40, Ed. Abril Cultural, São Paulo, SP.
[42] Gerrero L. (2003) Álcool ou gasoline? Você decide no posto. Revista Quatro Rodas 513, pp. 36–41, Ed. Abril Cultural, São Paulo, SP.
[43] Volkswagen. Manual do usuário do veículo VW Gol. São Bernardo do Campo, SP: Volkswagen do Brasil S.A.; 2000.
[44] Gômara R (2001) Identificação das características de distribuição de GN para os postos de service. Personal communication. Chief Representative of Aspro Compressors for NG, Rio de Janeiro, RJ.
[45] Blanco J (2004) Identificação da rede de gasodutos da CEG. Personal communication. VNG Market Development Manager, Companhia Estadual de Gás, Rio de Janeiro, RJ.
[46] Sobrinho CA (1999) Análise Comparativa do Desempenho de Compressores de Gás Natural; Características Técnico Econômicas. In *7th International Seminar on Natural Gas and LPG*, IBP, Rio de Janeiro, RJ.